Chapter 6.

Time of Flight Sensors

6.1. Overview

The sensors operational principles are the same for electromagnetic (radar, laser etc.) and active acoustic sensing.

Source of radiation is fed to a transmit antenna
- Tuned to the characteristics of the target (sometimes)
- Matched to the impedance of the medium to maximise coupling and efficiency
- Radiated by a directional antenna to increase the energy on target (sometimes)

Impacts on the target of interest
- Change in impedance results in re-radiation or scattering
- Re-radiation isotropic, random or directional

A small % of the power enters the receiver antenna
- Converted to an electrical signal
- Amplified and detected
6.2. Principle of Operation

Figure 6.2: Operational principles of a pulsed time-of-flight radar illustrate that the echoes from the nearer houses return to the radar first and that the echoes from the last two houses overlap and appear to the radar as a single return.

Time-of-flight is the principle mode of operation for most radar, laser and active acoustic devices. This technique uses the time between the transmission of a pulse and the reception of an echo is measured to provide range.

Because the round-trip time is measured there is a factor of 2 in the formula as shown below,

\[ R = \frac{v \Delta T}{2}, \]

where \( R \) – range (m),
\( v \) – wave propagation velocity (m/s),
\( \Delta T \) – round trip time (s).

6.2.1. Requirements

To operate efficiently a narrow beam must be formed to concentrate the transmitted energy, the transducer must be matched to the characteristics of the medium and the receiver must match the transmitter characteristics.
Some form of modulation must “mark” the carrier signal so that the round trip time can be measured. The figure below shows an amplitude modulated carrier showing the “bang” pulse and then a pair of echoes after a short delay.

![Image of modulated carrier signal]

Figure 6.3: Actual Received Signal Showing Carrier Modulation

It is not easy to process the modulated carrier, so in general it is detected (demodulated) before the timing information can be extracted. The figure below shows the envelope detected output.

![Image of detected signal]

Figure 6.4: Received Signal after Detection

### 6.2.2. Speed of Propagation for EM Radiation

Propagation speed is a function of the refractive index of the material

\[ v_{mat} = \frac{c}{N} = \frac{c}{\sqrt{\varepsilon_r}} \text{ m/s,} \]

where
- \( c \) – Speed of Light in a Vacuum \((3 \times 10^8 \text{ m/s})\),
- \( N \) – refractive Index of the material,
- \( \varepsilon_r \) – Relative dielectric constant of the material.

### 6.2.3. Speed of Propagation of Sound Waves

For acoustic propagation the velocity is a function of the bulk modulus and the density for sound waves as calculated below

\[ v_{mat} = \sqrt{\frac{B}{\rho}} = \frac{1}{\sqrt{K\rho}} \text{ m/s,} \]

where
- \( B \) – Bulk Modulus of the material,
- \( K \) – Compressibility of the material,
- \( \rho \) – Density of the material \((\text{kg/m}^3)\).
The bulk modulus of the material is defined as ratio of the applied pressure to the strain \( B = \frac{P}{(V_o - V_n)/V_o} \) Where \( P \) is the pressure and \( V \) is the volume.

Table 6.1: Speed of Sound in Different Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Speed (m/s)</th>
<th>Material</th>
<th>Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (STP)</td>
<td>343.2</td>
<td>Sea water</td>
<td>1450 - 1750</td>
</tr>
<tr>
<td>Air 0°C, dry</td>
<td>331.29</td>
<td>Methanol 30°C</td>
<td>1121.2</td>
</tr>
<tr>
<td>Nitrogen 0°C</td>
<td>334</td>
<td>Mercury</td>
<td>1451</td>
</tr>
<tr>
<td>Oxygen 0°C</td>
<td>316</td>
<td>Aluminium</td>
<td>5000</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>259</td>
<td>Copper</td>
<td>3750</td>
</tr>
<tr>
<td>Helium 0°C</td>
<td>965</td>
<td>Lead</td>
<td>1210</td>
</tr>
<tr>
<td>Water 0°C</td>
<td>1402.3</td>
<td>Steel</td>
<td>5250</td>
</tr>
</tbody>
</table>

Note that the temperature, the salinity and the density determine the variation in the speed of sound in the sea. This is addressed in Chapter 9. For time of flight sonar depth sounders, this variation in speed must be considered if accurate measurements are required.

6.2.4. The Antenna

The antenna acts as a transducer between transmission line propagation and free-space propagation.

During transmission it concentrates the radiated energy into a shaped beam that points in the desired direction and only illuminates the selected target and on reception it collects the energy reflected by the target and delivers it to the receiver.

The effectiveness of these two roles is described by the transmitting gain and the effective receiving aperture of the antenna.

In Sonar applications, the gain is known as the directivity index

Either one or two antennas can be used.

The gain and beamwidth are determined by the size of the antenna in terms of the wavelength radiated,

\[ G = \frac{4\pi A}{\lambda^2}, \]

where: \( G \) – Antenna gain,  
\( A \) – Frontal area of the antenna (m²),  
\( \lambda \) – Wavelength (m).
The antenna beamwidth is inversely proportional to the gain, so it can be estimated using the following simple formula.

\[
G \approx \frac{4\pi}{\theta_{3dB} \phi_{3dB}},
\]

where \( \theta_{3dB} \) and \( \phi_{3dB} \) are the beamwidths in orthogonal planes (rad).

\[
\theta_{3dB} \approx \frac{70\lambda}{d} \text{ deg},
\]

where \( \lambda \) is the wavelength (m) and \( d \) the antenna diameter (m).

The power pattern in the far field is proportional to the square of the field magnitude, \(|F(u)|^2\) for both sonar and radar antennas.

For a circular aperture the power pattern is

\[
P = \frac{J_1[(\pi D / \lambda) \sin \theta]^2}{(\pi D / \lambda) \sin \theta},
\]

where \( J_1 \) is the Bessel function of the first kind.

The half power beamwidth is \( \theta_{3dB} = \sin^{-1}(1.029\lambda / D) \) which corresponds (in the following figure) to \( u = 1.616 \).

For a rectangular aperture the transmitted (or received) power pattern as a function of the angle off boresight is

\[
P = \frac{\sin[(\pi l / \lambda) \sin \theta]^2}{(\pi l / \lambda) \sin \theta}.
\]

The half power beamwidth is \( \theta_{3dB} = \sin^{-1}(0.887\lambda / l) \) which corresponds to \( u = 1.393 \).
For the Sonar application, the electric field intensity is replaced by the sound pressure. In the following figure, the relationship between the aperture and the beamwidth is compared for three different transducer configurations.

**Figure 6.5: Antenna Beam Patterns**

**Figure 6.6: Total Beam Angle for (A) Ring Diameter, D (B) Line Length, L (C) Piston Diameter D**
Circular and Rectangular Antennas
Tracking and ranging antennas are generally symmetrical in the two axes so that they can generate a pencil beam pattern.

Cylindrical Antennas
Antennas and transducers for imaging or searching are generally asymmetrical so that they generate a broad beam in elevation and a narrow beam in azimuth.
6.2.5. The Transmitter

To mark the carrier so that the time-of-flight can be measured, the signal is “marked” in some way. This is known as modulation, and can be achieved in various ways:

- Amplitude modulation (AM)
- Frequency modulation (FM)
- Phase modulation (PM)
- Polarisation modulation

For most simple TOF sensors, the carrier is on-off amplitude modulated as shown in the figure.

![Figure 6.9: On-off Amplitude Modulation](image)

To maximise the number of pulses that strike the target in a given time, the pulse repetition frequency (PRF) is selected to be as high as possible while still catering for the maximum unambiguous range

\[ R_{\text{max}} = \frac{v T_{\text{max}}}{2} \]

where:
- \( R_{\text{max}} \) – Maximum unambiguous range (m),
- \( v \) – Velocity (m/s),
- \( T_{\text{max}} \) – Pulse repetition interval (1/PRF).

The pulse width \( \tau \) is selected to maximise the amount of energy transmitted (average power) while still giving the required range resolution.

![Figure 6.10: Transmitted and Received Pulse Trains](image)
It is possible to use “pulse compression” techniques to increase the average power while still maintaining the required range resolution. This is covered in Chapter 12.

**Radar Transmitters**

For long range applications, the peak transmit power can be extremely high, many MW for surveillance radars. Microwave tubes such as Magnetrons, Klystrons and Travelling Wave Tubes (TWT’s) are generally used to produce the high powers required for radar operation.

The first Magnetron ever made is shown in the figure below. It was made by Randall and Boot of the Physics Department of Birmingham University in February 1940 and had important implications in the successful use of airborne radar during WW II.

![Figure 6.11: The First Magnetron (without magnets)](image1)

Magnetrons are still found in most low-cost radar systems because they are cheap and extremely efficient. The magnetron shown below is typical of the genre.

![Figure 6.12: Magnetron from Microwave Oven (with magnets)](image2)

For short range applications at high frequency (>10GHz), solid state oscillators using Gunn or IMPATT diodes are often used. These are two-terminal devices which are placed within a resonant cavity where they can be biased to exhibit the appropriate behaviour to sustain high-frequency oscillations.
For operation at lower frequency, voltage controlled oscillators (VCO’s) using FET’s or high electron mobility transistors (HEMT’s) are used. These use the more conventional amplifier and feedback configuration shown in Chapter 2 to produce oscillations.

Figure 6.13: Millimetre Wave Transmitter Oscillators

Figure 6.14: Power Outputs from Various Solid State Transmitters
**Ultrasonic Transmitters**

For short range applications, most ultrasonic transmitters are made from a piezoelectric material. Such materials exhibit a change in size proportional to the applied electric potential.

Natural piezoelectric crystals include Quartz, Rochelle Salt (sodium potassium tartarate) and Tourmaline.

Ferroelectric crystals and ceramics of the barium titanate type and ferromagnetic ceramics of the ferrite type are also used as transducers.

These materials exhibit changes in length proportional to the square (or higher power) of the polarisation, and exhibit changes in length which are a function of an applied electric or magnetic field. They are equivalent to piezoelectric and piezomagnetic materials.

![Figure 6.15: Ultrasound Sonar](image)

**Laser Transmitters**

Laser transmitters rely on the quantum-mechanical operation of carefully doped PN junctions (diodes) to produce coherent radiation in the IR or visible region when biased by a short current pulse. As shown in the figure below, the cleaved ends of the diode function as mirrors to form a cavity within which the radiation is constrained as it is reflected back and forth.

![Figure 6.16: Solid State Laser Transmitter](image)
6.2.6. The Receiver (Matched Filtering and Demodulation)

The receiver frequency response is matched to the transmitter modulation pulse characteristics to maximise the peak signal to noise ratio (SNR).

If the bandwidth of the receiver is wide compared to the bandwidth of the transmitted pulse, then noise introduced by the extra bandwidth reduces the SNR.

If the receiver bandwidth is too narrow, it will “ring” when it receives a pulse. As a rule of thumb for pulsed measurement systems, the receiver bandwidth $\beta$ is equal to the reciprocal of the pulse width.

$$\beta = \frac{1}{\tau}$$

The following figures show simulation results for an ultrasonic system in which the filter bandwidth is adjusted to illustrate this effect.

(a) [Graph of Transmit Signal and Filtered Echo]

(b) [Graph of Transmit Signal and Filtered Echo]

Figure 6.17: Effect of Changing the Bandwidth of a Matched Filter showing (a) the Matched Bandwidth and (b) the Ringing because the Bandwidth is too Narrow

For other waveforms (pulse compression etc), the matched filter form must be calculated for the specific waveform and the type of noise. This will be addressed in Chapter 12.
After filtering, the signal is demodulated (or detected) to extract the timing information from the carrier wave. For basic time-of-flight sensors, this is generally encoded in the amplitude of the carrier (AM).

In most laser sensors the reflected light is detected directly using a fast light-sensitive diode (PIN or avalanche photo diode).

### 6.3. Range Measurement

The range to a target is determined by running a clock from the moment a pulse is transmitted until the echo is received.

The echo is detected when the received signal (at the output of the detector) exceeds a pre-set threshold level as shown in the figure.

![Figure 6.18: Measuring Range](image)

The threshold level is set so that the probability of a false alarm (noise alone exceeding the threshold) is low, while there is still a good probability that the signal + noise will exceed the threshold.

The threshold level can be adjusted automatically, or the receiver gain can be adjusted automatically to compensate for the $R^{-4}$ signal-level characteristic. This is called sensitivity time control (STC). It should not be confused with automatic gain control (AGC) which performs a different function.

![Figure 6.19: Adjustable Threshold to Accommodate Propagation Losses](image)
6.3.1. Pulse Integration

Pulse integration may be used to decrease the false-alarm rate and to improve the measurement accuracy. This can be achieved by averaging a number of pulses before thresholding, or by averaging the measured range and discarding outliers.

![Figure 6.20: Pseudo Pulse Integration](image)

Integration of pulses requires some sort of storage device. In the old days this was achieved by using a long persistence phosphor on the cathode ray tube radar display combined with the integrating properties of the eyes and brain of the operator.

Modern ranging devices often use digital memory and high-speed signal processing techniques to perform the integration function as shown in the figure below.
Digital processing of radar signals is limited by the sample rate of the required Analog to Digital (ADC) converters with sufficient dynamic range.

If the radar gate size $\delta R = 10\text{m}$, the sample time for the Sample and Hold should be

$$\tau = \frac{2\delta R}{c} = 67\text{ns},$$

and the ADC must clock at 15MHz.

It is not practical to use this integration technique for very short-range high-resolution techniques. For example a laser radar that has a gate size of 10mm would require a sample time of 67ps and a clock rate of 15GHz.
6.3.2. Time Transformation

Cost sensitive applications such as industrial level sensors and commercial laser range finders use an analogue technique known as “time transformation” to stretch the return time as this leads to a reduction of their clock frequency and ADC requirements.

![Diagram](image)

**Figure 6.23: Integration by Time Transformation**

Time transformation is only required for radar and laser devices because of the high speed of EM propagation. This is not required for sonar devices in air (or even in water) as the speed is sufficiently low.

Time transformation has the added advantage of integrating repetitive signals automatically because each point on the repeated echo is sampled many times and integrated through a low-pass filter.

Typical transformation ratios of (1:100000) are common in short range level measurement applications as these will transform a time-of-flight sensor that uses EM radiation into the equivalent of an acoustic system.
6.4. The Radar Range Equation

The radar range equation determines the maximum range at which a target can be detected. It takes on many forms depending on what type of system is being described and it can be used to describe Lasers, Radars or Acoustic Systems.

It is generally optimistic because of losses not accounted for and higher than expected noise levels reduce the performance of actual systems.

If the power transmitted by the sensor is $P_t$ through an isotropic radiator (one which radiates uniformly in all directions) then the power density at range $R$ from the transmitter will be equal to the transmitted power divided by the surface area $4\pi R^2$ of an imaginary sphere of radius $R$.

\[
\text{Power density from an isotropic antenna} = \frac{P_t}{4\pi R^2} \quad \text{Watt/area}
\]

The gain $G_t$ of an antenna is the measure of the increased power in the direction of the target compared to the isotropic case.

The power density $S_t$ at the target is

\[
S_t = \frac{P_t G_t}{4\pi R^2} \quad \text{Watt/area.}
\]

The target intercepts a portion of this power and re-radiates it in various directions.

The measure of the proportion of the incident power re-radiated in the direction of the receiver is denoted as the target backscatter coefficient $\rho$ for a laser radar with a spot size (footprint) smaller than the target, or as the radar cross-section $\sigma$ for either a laser or microwave radar if the beam footprint is larger than the target.
The radar cross section, RCS, has units of area and is characteristic of a particular target and its orientation.

The power density back at the receiver antenna will be

\[ S_r = \frac{P_i G_t \sigma}{4\pi R^2} \quad \text{Watt/area.} \]

For an effective area of the receiving antenna \( A_e \) defined as the ratio of the received power at the antenna terminals to the power density of the incident wave. Then the power received by the sensor is

\[ S = \frac{P_i G_t \sigma}{(4\pi)^2} A_e \quad \text{Watt.} \]

The gain \( G_r \) of a lossless antenna is related to its effective aperture by the expression

\[ G_r = \frac{4\pi A_e}{\lambda^2}, \]

where \( \lambda \) is the wavelength (m).

The effective aperture of antennas that are large in terms of wavelength \((d>20\lambda)\) can approach the physical antenna size. Substituting for \( A_e \)

\[ S = \frac{P_i G_t \sigma}{(4\pi)^2} \frac{G_r \lambda^2}{4\pi} = \frac{P_i G_t G_r \lambda^2 \sigma}{(4\pi)^4} \quad \text{Watt.} \]

For a monostatic sensor (same receive and transmit antennas) \( G_t = G_r = G \)

\[ S = \frac{P_i G^2 \lambda^4 \sigma}{(4\pi)^3} \quad \text{Watt.} \]

To account for losses, these are lumped together to reduce the amount of power received and are denoted \( L \) where \( L<1 \)

\[ S = \frac{P_i G^2 \lambda^4 \sigma L}{(4\pi)^3} \quad \text{Watt.} \]

The maximum detection range \( R_{\text{max}} \) is the range at which the received power just equals the minimum detectable signal \( S_{\text{min}} \). Equating \( R_{\text{max}} \) for \( S = S_{\text{min}} \).

\[ R_{\text{max}} = \left[ \frac{P_i G^2 \lambda^2 \sigma L}{(4\pi)^3 S_{\text{min}}} \right]^{\frac{1}{2}} \quad \text{metres} \]
6.4.1. Example of Radar Detection Calculation

Determine the maximum detection range of a maritime surveillance radar with the following characteristics

Find the maximum detection range of a maritime surveillance radar with the following specifications

- Gain 34dB
- Transmit peak power 2kW \( (10\log_{10}2000 = 33\text{dBW}) \)
- Frequency 10GHz
- Losses 5dB
- Target RCS 5sqm \( (10\log_{10}5 = 7\text{dBsqm}) \)
- Minimum detectable signal \( 1.6\times10^{-13} \text{ W} \ (-128\text{dBW}) \)

Start by converting everything to dB as shown

Apply the radar range equation that has been written for dB values

\[
S_{db} = P_{db} + 2G_{db} + 10\log_{10} \left( \frac{\lambda^2}{(4\pi)^2} \right) + \sigma_{db} - L_{db} - 40\log_{10} R
\]

Plot the received signal \( S_{db} \) on a semilogx plot along with the minimum detectable power as shown.

![Graphical Solution to the Radar Range Equation](image)

**Figure 6.24: Graphical Solution to the Radar Range Equation**
6.4.2. Receiver Noise

Noise is the unwanted electromagnetic energy that interferes with the ability of the receiver to detect the wanted signal. It may enter the receiver through the antenna along with the desired signal or it may be generated within the receiver.

As discussed in an earlier lecture, noise is generated by the thermal motion of the conduction electrons in the ohmic portions of the receiver input stages. This is known as Thermal or Johnson Noise.

Noise power $P_N$ is expressed in terms of the temperature $T_o$ of a matched resistor at the input of the receiver

$$P_N = kT_o\beta \quad \text{Watt},$$

where: $k$ – Boltzmann’s Constant $(1.38 \times 10^{-23} \text{ J/K})$,
$T_o$ – System Temperature (usually 290K),
$\beta$ – Receiver Noise Bandwidth (Hz).

The noise power in practical receivers is always greater than that which can be accounted for by thermal noise alone.

The total noise at the output of the receiver $N$ can be considered to be equal to the noise power output from an ideal receiver multiplied by a factor called the Noise Figure, $NF$.

$$N = P_N NF = kT_o \beta NF \quad \text{Watt}.$$

6.4.3. Detection Range in terms of Output SNR

Generally the target detection, $P_d$, and false alarm, $P_{fa}$, probabilities are given in terms of the output $SNR$.

The minimum received signal can be written in terms of the output $SNR$ required to achieve a specific $P_d$ and $P_{fa}$ and the pulse width $\tau$

$$\left(\frac{S}{N}\right)_{out} = \left(\frac{S_{\text{min}}}{N}\right)_{in} \beta\tau = \frac{S_{\text{min}}\beta\tau}{kT_o NF},$$

$$S_{\text{min}} = \left(\frac{S}{N}\right)_{out} \frac{kT_o NF}{\tau}.$$

Substituting $S_{\text{min}}$ back into the radar range equation to obtain the detection range

$$R_{\text{max}} = \left[ \frac{PG^2\lambda^2\sigma L\tau}{(4\pi)^3 kT_o (S/N)} \right]^{1/4} \text{ metres}.$$
6.4.4. Pulse integration and the probability of detection

If all of the received power from $K$ radar returns is integrated perfectly, then the effective $SNR$ is equal to $K$ times the single pulse $SNR$ for coherent (pre-detection) integration.

Most radars perform their integration on the video signal after envelope detection as it is much easier to achieve. This is known as non-coherent integration. This is not as effective as coherent integration and the improvement in effective $SNR$ is only about $K^{0.8}$ for white thermal noise.

For correlated noise the effectiveness of integration is reduced and is a function of the correlation time and the number of pulses integrated (the integration time).

The following probability density function (PDF) shows the effect of integration on the noise and the target + noise distributions for a non-fluctuating target echo.

Note that the means of the PDFs remain unchanged, but their separation (in terms of variance) increases.

For a given threshold, the probability of detection $P_d$ increases and the probability of false alarm $P_{fa}$ decreases.

These probabilities are generally evaluated numerically and displayed graphically as shown in the figure below.

Generally, a $P_d$ and $P_{fa}$ are selected for a particular application. The required $SNR$ is then determined from the graph. This $SNR$ is then reduced by the effective integration gain $10\log_{10}(K)$ for coherent integration and $8\log_{10}(K)$ for non-coherent (also know as post-detection) integration where $K$ is the number of pulses integrated before being plugged into the range equation.
Note that any fluctuations in the target RCS has a major influence on the $P_d$ and $P_{fa}$ or on the detection range. These effects are dealt with in Chapter 11.

![Detection Probability Curves](image)

**Figure 6.26: Detection Probability Curves**

### 6.5. Problems with TOF Measurement

Electromagnetic waves travel very fast with $\delta T = 6.6$ns/m. This means that high data rates are possible but it is difficult to obtain measurement accuracy much better than 1m.

Acoustic signals travel much more slowly $\delta T = 6$ms/m (in the air). Data rates are much lower but good accuracy (<1mm) is possible with appropriate temperature compensation if the medium is still.

#### 6.5.1. Range Ambiguity

Echoes from large targets at long range may be received after the next pulse has been transmitted. This problem can be eliminated by transmitting at different pulse repetition frequencies.
6.5.2. Beamwidth Ambiguity

Any object within the beam (or the sidelobes) will return an echo and as the actual target range may vary considerably across the beamwidth, there may be significant range uncertainty.

Targets with large cross sections will dominate the return echo even if they are not in the centre of the beam.

Compared to the possible range resolution, angular resolution of typical sensors is poor. It is determined by the effective aperture (in wavelengths) of the radiating antenna, and so is determined to a large extent by the transmission frequency.

Synthetic aperture, monopulse or interferometry can also be used to improve the angular resolution using techniques that are discussed in Chapters 17 and 20.
6.6. Radio Altimeters

Under certain conditions the radar cross section of a target may be a function of range.

![Figure 6.27: Radio Altimeter](image)

In the case of a radar altimeter (shown above), the cross section $\sigma$ is proportional to the area of the beam footprint on the ground.

For a beamwidth $\theta$, the area will be

$$A = \frac{\pi d^2}{4} = \frac{\pi (R\theta)^2}{4}.$$

The scale factor $\sigma^o$ is called the target reflectivity and is defined as the radar cross section per unit area. The RCS is found by taking the product of the reflectivity and the area as discussed in detail in Chapter 10.

$$\sigma = \sigma^o A = \frac{\pi (R\theta)^2 \sigma^o}{4}.$$

Substituting into the basic radar range equation reduces the received signal power to a function of $R^2$

$$S = \frac{P_i G^2 \lambda^2 \theta \sigma^o L}{4^4 \pi^2 R^2}.$$

Because typical radar cross sections are large, and ranges are short, altimeters can transmit low average powers (100-500mW), and if required operate using low probability of intercept (LPI) spread spectrum waveforms.

**Typical Specifications (BAe Systems GRA2000)**

- **Size:** 3.123×3.0×8.5in
- **Weight:** 4lb
- **MTBF:** >8000hours
- **Altitude:** 0-5000ft exceeds +/-2ft or 2%
- 5-35,000ft exceeds +/-50ft or 1%
6.7. Cruise Missiles and Standoff Weapons

The formal definition of a cruise missile or standoff weapon is a dispensable, pilotless, self-guided, continuously powered, air breathing warhead delivery vehicle that flies like a plane.

Standoff weapons generally operate over much shorter ranges, hundreds of kilometres, than cruise missiles that can operate over thousands of kilometres.

Unlike ballistic missiles, cruise missiles require continuous guidance since both the velocity and direction of flight can be unpredictably altered by local weather conditions or unexpected changes in the performance of the guidance system.

A ballistic missile is guided for the first 5 of twenty minutes that it takes to fly 5000km; a cruise missile that flies at a subsonic speed would require at least 6 hours of continuously guided flight to cover the same distance.

Guidance errors that integrate with time would thus be 100 times larger for a cruise missile than for a ballistic missile operating at comparable range.

To obtain the necessary location information accuracy, a cruise missile generally uses a combination of inertial guidance that can be augmented by GPS when it is available and some form of map stored in its memory that can be used to correlate its position.

The earliest cruise missile was the German V-1 “buzz bomb” of World War II. However it and the US Matador, Regulus and Snark, and the Russian Shaddock missiles had no way of correlating their positions after launch.

Modern cruise missiles generally use one of two correlation techniques
- Terrain contour matching (tercom)
- Area correlation
6.7.1. Terrain Contour Matching (Tercom)

Patented in 1958 it relies on the simple fact that the altitude of the ground above sea level varies as a function of location.

A terrain altitude map with 2kmx10km with a cell size of 100x100m would require only 2000 points. So even if 20 such maps were required, the memory requirements are miniscule.

As the missile flies into one of the mapped areas, altitude readings obtained from an on-board radio altimeter are compared with the stored data to determine the missile position to the accuracy of one cell. The autopilot is then instructed to make the appropriate correction.

Inferences about drifts in the inertial system and prevailing winds etc. can be made at each stage, so subsequent maps may be smaller and higher resolution, leading to pinpoint targeting.
6.7.2. Area Correlation

Instead of using the ground height based on measurements using radio altimeters, area-correlation techniques correlate active radar or passive radiometric scanned images with aerial photographs of the target area.
A reference image is made that includes point and line targets (a) is correlated with a raw radar map of the area (b) to produce a good unambiguous correlation peak as shown in the figure below.

Figure 6.32: Correlation output from a reference image made up of point targets and a section of wall, and a raw radar image shows a single unambiguous peak.

6.8. References